Express Mail Label No. EV041360414US

PROTECTION CIRCUIT FOR A BATTERY CELL

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] Not applicable.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

[0002] Not applicable.

BACKGROUND OF THE INVENTION

Field of the Invention

[0003] The present invention generally relates to protecting battery cells from various fault conditions and unequal cell performance during normal operation. More particularly, the invention relates to a cell protection circuit that provides over-current protection to battery cells.

Background Information

[0004] Batteries are useful for a variety of purposes, but generally must be operated in accordance with various criteria to ensure the safety and reliability of the battery and the device for which it provides power. The protection circuit described herein has been developed for use in connection with lithium batteries that are used in downhole tools. Such tools may be used for open hole logging and/or drilling purposes. Although the following background information and description of the protection circuit may be presented in the context of protecting high voltage, lithium battery packs, the protection circuit is useful for batteries used in a variety of other applications and for non-lithium battery types, particularly those that have similar safety and reliability concerns. Accordingly, the disclosure and claims which follow are not limited to the context in which the protection circuit is discussed below.

[0005] By way of definition, a "cell" is an individual location where chemical energy is converted into electric energy. A "battery" or "battery pack" is a collection of one or more cells connected in series or in parallel to produce more current, voltage or power than is provided by an individual cell.

[0006] The selection of battery type and configuration for downhole tools is influenced by various considerations. Downhole tools are typically packaged so as to have a diameter less than four inches so as to fit within a standard 8-1/4 inch diameter drill pipe. For obvious reasons, space is therefore at a premium for a downhole tool and thus battery packs should be as small as possible. Further, downhole tools usually experience relatively high temperatures presenting a potential hazard for the tool and its battery. It is not uncommon, for example, for the tool to operate at temperatures exceeding 150 °C or even 175 °C. Also, the relatively high cost (labor and materials) of a seismic or drilling operation makes it desirable to reduce cost whenever possible. In light of these considerations, lithium cell chemistry is used in a majority of downhole tool applications today when surface power is not provided by a wireline or other means. Lithium cells, and particularly, lithium thionyl chloride ($Li/SOCl_2$) cells provide high energy densities (i.e., a relatively large amount of energy given the size and weight of the cell when compared to other types of cells) and excellent high temperature performance. Thus, relative to many other types of cells, lithium cells last longer and operate better at higher temperatures with lower total cost.

[0007] Despite the advantages of lithium cells, they are not problem free. For instance, the discharge profile of a lithium cell must be carefully controlled to obtain the available energy from the cell and prevent hazardous conditions. Two of the most prevalent conditions that interfere with optimal $Li/SOCl_2$ cell performance are excessive anode "passivation" and cathode "freeze-over." Anode passivation refers to the formation of a layer of lithium chloride (LiCl), which is also

known as solid electrolyte interphase (SEI), on the anode surface. Cathode freeze-over refers to the formation of LiCl discharge products in the outer portion of the cathode which blocks access to unused reaction sites.

[0008] A thin SEI layer is always present on the surface of the anode. This layer is formed as a result of the reaction between the lithium and the thionyl chloride electrolyte in the cell, and the layer begins to form as soon as a cell is filled with electrolyte. The LiCl generally is a desirable feature for long term storage of such cells because it helps to minimize or prevent self-discharge. It is only when the cell is placed into service that passivation becomes a problem. Anode passivation is responsible for the condition known as "voltage delay," which is the initial drop in potential observed when a load is first placed on a cell. The voltage drop is caused by the SEI layer which acts as a series resistor. As current flows through the cell, the SEI layer begins to evaporate resulting in an associated increase in cell terminal voltage. This process is called "depassivation." In a freshly manufactured cell, the drop in running potential may last for less than a second, but in a heavily passivated cell (i.e., a cell with thick SEI layer), the voltage may drop below its nominal voltage (e.g., 3 volts) for an extended period of time.

[0009] As noted above, the performance of Li/$SOCl_2$ cells also can be detrimentally affected by cathode freeze-over which is the formation of LiCl discharge products in the outer portion of the cathode to the extent that it blocks the electrolyte's access to unused reaction sites. The discharge of Li/$SOCl_2$ cells results in the formation of LiCl in the cathode. If the cell is discharged at low rates (e.g., a current density of less than 2 milliamps per square centimeter), the LiCl will be evenly distributed throughout the carbon cathode, which results in efficient use of the active sites available for the reduction of $SOCl_2$. At discharge rates greater than 2 mA/cm^2, the reduction of $SOCl_2$ occurs predominantly on the outer surfaces of the cathode. The outer surface of the cathode

effectively "freezes over" with LiCl, and the inner active surfaces become inaccessible. Unlike passivated anodes, which can be recovered via a depassivation process, cathodes that have been frozen over are irreparably damaged and capacity loss will result.

[0010] As noted above, passivated cells can be depassivated. This can be accomplished by placing the cells under load in a predetermined manner. Initially, the cell voltage will drop (below 3 V) due to the passivation, but gradually increase as the cell becomes unpassivated. One suitable way to depassivate a pack of cells is to place the cells under a light current load and then, as the voltage increases due to depassivation, increase the current draw on the pack.

[0011] For many cells, the voltage will begin to rise in about 15 minutes. A severely passivated cell may have a cell voltage below 3 V for a prolonged period of time (e.g., more than one hour). Any load that results in a cell voltage below 3 V for a prolonged period of time may cause cathode damage and reduce cell capacity. Batteries used for high voltage downhole tools typically are constructed from dozens or even a hundred or more series-connected lithium cells. Depassivating a pack of 100 cells might successfully depassivate most of the cells in the pack, but some cells may remain depassivated due to variations between individual cells. It is difficult to determine whether a few cells out of a hundred are passivated. Thus, as the current load is increased during the depassivation process, some cells that are still passivated will experience an increasing current demand. Because of the passivation that remains on such cells, the voltage of such cells will drop as the current load is increased. As explained below, this voltage drop can be harmful to the cell.

[0012] Cell voltage generally decreases as the current demand on the cell increases. Also, cell voltage will generally decrease as a cell ages and nears the end of its useful life. Most cell manufacturers recommend that their cells not be discharged to a point where the cell voltage is

below a minimum level (e.g., 2 V). Forcing a cell below 2 V may cause bulging of the cell due to the build up of gaseous discharge products in the cell. It is also widely known that lithium cells exhibit safety concerns when the cells are discharged into reversal (the cell voltage reverses polarity). Besides cell reversal, the cells can also vent various gasses from a short circuit at elevated temperatures. Manufacturers also warn that excessive loading of 3 or more cells in series has been known to result in venting caused by cell reversal.

[0013] Accordingly, because current is increased during the depassivation process and the voltage of passivated cells decreases with increases in current, it is possible to over drive a passivated cell during the depassivation process. This is particularly problematic for large strings of cells in a battery in which it is difficult to detect a few passivated cells out of numerous other depassivated cells in the battery. Over driving a passivated cell in this manner may cause such problems as cell reversal and off gassing. A solution to this problem is needed.

[0014] A similar concern is also present during the normal use of a battery. The battery provides the current needed by the device (e.g., downhole tool). If one or more of the cells in the battery are passivated, the cell voltage for such cells may drop to a dangerous level. Also, a cell that is not passivated, but is nearing the end of its useful life, may be unable to provide the necessary current at an acceptable voltage level. As such, the voltage of such a nearly spent cell may be forced to a dangerously low level at the current level demanded by the load.

[0015] In summary, there are various reasons why a cell may be forced to an undesirable or dangerously low voltage level. Several of such reasons are given above. Regardless of the reason, a way to guard against such a condition is needed.

BRIEF SUMMARY OF THE PREFERRED EMBODIMENTS OF THE INVENTION

[0016] The problems noted above are solved in large part by a protection circuit which couples to and protects a cell. The protection circuit generally limits the current that can flow through the cell when the voltage across the cell falls to a predetermined minimum threshold. By limiting the current through the cell in this situation, the voltage on the cell will not fall below the minimum safe level.

[0017] In accordance with one embodiment of the invention, the protection circuit includes a transistor coupled in series with the cell and a bypass device coupled to both the transistor and the cell and in parallel with the transistor and cell. The transistor preferably comprises a metal oxide semiconductor field effect transistor ("MOSFET") and more preferably either an n-channel, enhancement mode MOSFET or a p-channel, enhancement mode MOSFET. The bypass device preferably comprises a diode that permits current to conduct around the cell being protected when the transistor limits the current through the cell.

[0018] If desired, a delay element can be included in the protection circuit to slow the change in voltage across the transistor with short duration pulse loading. The delay element may comprise a resistor coupled to a capacitor to provide a desired R-C time constant. The delay element increases the performance of the cell by not activating the current limiting function of the transistor.

[0019] In a battery comprising a plurality of cells, each cell can have its own protection circuit, thereby providing improved protection in a multi-cell battery. The protection circuit, in fact, can be made in the form of a disk or wafer that physically is disposed between adjacent cells in a string of serially connected cells. It is also possible to include the protection circuit within each cell. In

this way, the cell's voltage can be maintained at a safe level. These and other advantages will become apparent upon reviewing the following disclosure.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] For a detailed description of the preferred embodiments of the invention, reference will now be made to the accompanying drawings in which:

[0021] Figure 1 shows an embodiment of a protection circuit using an N-channel MOSFET transistor for use with a cell;

[0022] Figure 2 shows a first alternative embodiment of the protection circuit using a P-channel MOSFET transistor;

[0023] Figure 3 shows a second alternative embodiment of the protection circuit; and

[0024] Figure 4 shows a mechanical layout illustrating the physical location of the protection circuit in relation to two adjacent cells.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0025] Referring to Figure 1, a protection circuit 50, constructed in accordance with a preferred embodiment of the invention, is shown for protecting an individual cell 52. Preferably, each cell in a serially connected string of cells includes its own protection circuit connected as shown in Figure 1. The form of the protection circuit 50 may vary from that shown; the particular circuit shown in Figure 1 is only one of numerous possible circuits for implementing the invention.

[0026] As shown in Figure 1, the protection circuit 50 preferably includes at least two parts—a cell voltage-dependent current limiter 54 and a current bypass device 56. Preferably, the current limiter 54 comprises a transistor and the bypass device 56 comprises a diode. In accordance with the preferred embodiment of Figure 1, the transistor 54 is an n-channel enhancement metal oxide semiconductor field effect transistor (MOSFET). The source (S) of the MOSFET 54 connects to

the negative terminal of the cell 52 to be protected. The gate (G) of the MOSFET connects to the positive terminal of the cell 52. The drain (D) connects to the preceding cell (not shown) in a series of cells. The positive terminal of the cell 52 also connects to the cathode of the diode 56 and connects to the subsequent cell (not shown) in the series connection of cells. The anode of the diode 56 connects to the drain D of the MOSFET 54. The protection circuit 50 shown in Figure 1 provides protection for the cell 52 as will be described below. Preferably, as noted above, each cell in a battery would have its own protection circuit. Thus, a battery with 100 cells would have 100 protection circuits 50. Although, a separate protection circuit preferably is included for each cell in a battery, this is not a requirement in that not every cell in a battery need have a protection circuit 50.

[0027] The operation of the protection circuit 50 will now be described with reference to Figure 1. As shown, the transistor 54 is connected in series with the electrical current path through the cell 52 to be protected. The circuit 50 is designed to restrict current through the cell when the cell voltage falls to a predetermined minimum level, that is deemed the minimum safe operating voltage for the cell. This is accomplished by selecting a MOSFET 54 that has a threshold voltage equal to, approximately equal to or slightly greater than the cell's minimum target voltage. If, for example, the minimum target cell voltage is 2 V, then the MOSFET selected or designed to use as transistor 54 is a MOSFET with a 2V threshold, or a MOSFET with a threshold of approximately 2 V or slightly greater than 2V (e.g., 2.1 V).

[0028] Because the cell 52 is connected between the gate and source terminals of the MOSFET 54, during normal operation (i.e., no fault condition) the cell voltage (being greater than the MOSFET's threshold voltage) biases the transistor into its fully on state. The fully on state is the state in which the MOSFET is in its low resistance mode, as would be understood by those of

ordinary skill in the art. While in this state, the cell is permitted to source as much current as is demanded by the load (not shown) providing an associated cell voltage. In this normal state, the diode 56 does not conduct current.

[0029] If, however, the cell voltage falls to the predetermined minimum level, the state of transistor 54 changes to its linear mode of operation in which the drain voltage varies to maintain a constant gate-to-source voltage. The cell voltage may fall to the minimum target level because the cell is passivated and the internal resistance of the cell caused by the passivation layer causes the cell's terminal voltage to be lower for a given current level than it would have been if it was not passivated. Also, the cell voltage may drop excessively because the cell has simply reached, or is approaching the end of, its useful life and does not have the capacity to provide the necessary current without a larger drop in cell voltage. Regardless of why the cell voltage has fallen to the minimum target level, once at that selected target voltage level (e.g., 2V), the MOSFET 54 changes from being fully on to being in the linear region of its operation. This MOSFET state change is caused by the voltage across the cell being used as the gate voltage for the MOSFET 54. When that cell voltage (and thus gate voltage) reaches the threshold voltage of the transistor, the transistor enters its linear region of operation. When the current demand exceeds the cell's ability to maintain a predetermined minimum terminal voltage, the transistor enters the linear operating region thereby pinching off the cell current to the extent needed to maintain a minimum cell voltage (i.e., the threshold voltage). While in this state, the transistor's drain-to-source resistance increases with increasing current into the circuit to maintain the cell's voltage at an acceptable level. As such, the transistor functions as a cell voltage dependent current limiter. Any other device or circuit that can perform this function is acceptable.

[0030] At this point where the transistor is operating in its linear operation region and operating as a current limiter, the bypass diode 56 turns on and begins conducting in parallel with the MOSFET 54 and cell 52. As such, total current I_T into the circuit divides through the circuit into two portions I_A and I_B. The I_A current portion flows through the MOSFET 54 and cell 52 and the I_B portion flows through the diode 56. The drain-to-source resistance of the MOSFET 54 adjusts itself automatically to maintain a relatively constant I_A current level through the cell and a current level that guarantees an acceptable cell voltage (the minimum target voltage for the cell). If I_T exceeds the current level desired for I_A, the excess current (I_B) is caused to flow through the diode 56. The diode thus functions as a bypass element to permit a bypass route for excess current to flow so that the cell voltage can remain at an acceptable level. As a result, the cell is allowed to supply as much power to the load as is possible without exceeding its safe operating condition for its current state-of-charge.

[0031] An alternative embodiment of the protection circuit is shown in Figure 2. The protection circuit 60 in Figure 2 is similar in function to the circuit 50 in Figure 1. The main difference is that, whereas an n-channel enhancement mode MOSFET was employed as the cell voltage dependent current limiter in circuit 50, a p-channel enhancement mode MOSFET 64 is used in circuit 60. As shown in Figure 2, the drain of the MOSFET 64 couples to the cathode of bypass diode 66 (which functions similar to bypass diode 56 in Figure 1). The source of the MOSFET 64 connects to the positive terminal of the cell 52 being protected, while the MOSFET's gate couples to the cell's negative terminal and the diode's anode as shown. Conceptually, the protection circuit 60 functions much the same way as the protection circuit 50 of Figure 1. As such, a description of operation of circuit 60 is unnecessary and not specifically included herein.

[0032] In some downhole tool and other applications, it is desirable to be able to extract a short duration "burst" of energy from a battery. In downhole nuclear magnetic resonance (NMR) applications, such bursts might be on the order of 900 mA for less than one second with a 2-5 second recovery period between pulses. Such high current bursts would cause the protection circuits 50 and 60 for each cell to be activated to reduce the current through each cell. If this were to occur, the performance of the battery during the high current bursts would suffer because of the presence of the protection circuits. However, the high current bursts are of short enough duration so as generally not to harm the cells. Thus, the protection circuits can be modified to permit the protected cells to provide the desired high current bursts.

[0033] The modification to the protection circuit is to add one or more components that introduces a time delay to the protection capability during pulsed load conditions. An example of a protection circuit that provides a suitable time delay is shown in Figure 3. The protection circuit 70 of Figure 3 is largely the same as that of Figure 2. The difference, however, is that a resistor (R) and a capacitor (C) have been added to the circuit. The resistor R couples between the negative terminal of the cell 52 and the gate of the MOSFET 64. The capacitor C couples between the positive terminal of the cell and the gate of the MOSFET. The interaction between the resistor and capacitor introduces a time delay with a time constant that is a function of the values of the resistance of the resistor and the capacitance of the capacitor, as readily understood by those skilled in the art. As such, the protection afforded by the circuit 70 is delayed from being triggered by any desired amount of time as dictated by the resistor-capacitor combination selected. Thus, the cell is able to deliver additional current under short duration pulsed conditions without permanent cell degradation. This is particularly beneficial because the protection circuitry results in an increased

loss of power when activated. As a result, the endurance of the battery is improved as acceptable current pulses may be delivered to the load without activating the protection circuitry.

[0034] Figure 4 illustrates one out of numerous possible way to package the protection circuit of the various preferred embodiments described above with cells in a battery. Two cells 52a and 52b are shown in series. Respectively, each cell has a positive terminal 82a, 82b and a negative terminal 80a, 80b. The positive terminal 82b of cell 52b generally couples to the negative terminal 80a of cell 50a. The protection circuit can be fabricated in the form of a disk or wafer 90 that is inserted between the cells. Wafer 90 as shown is used to protect cell 52b. Electrical connections can be made between the wafer 90 and the cell 52b in accordance with the schematics of Figures 1-3.

[0035] The preferred embodiments of the cell protection circuit described above offer a variety of advantages over conventional protection schemes. For example, failure of any one component in the protective circuit itself may result in a degradation of the protective circuit's performance, but such a failure generally is benign in nature. For example, the drain-to-source short circuit of a power MOSFET is the most likely failure mode for this circuit. The short circuit of the MOSFET transistor will result in a loss of its local protection circuit, however, protection would still be provided by the current limit set by the strongest cell in a string of serially connected battery cells.

[0036] Further, an open circuit MOSFET failure removes the corresponding cell from the battery circuit. Nevertheless, the battery itself would continue to operate with its voltage reduced by one cell potential, and the current generated by the remaining series cells would be conducted through the bypass diode of the disconnected cell.

[0037] An open circuit bypass diode failure removes the possibility of conducting battery current around a weak cell, but does not prevent operation of the cell's protection circuit. This

condition results in the maximum current of the series string of cells being limited to that of the affected cell.

[0038] A short circuit bypass diode failure results in the discharge of the affected cell until depleted. The protection circuit limits the discharge rate to a safe value, and tapers the current level to zero before an unsafe depth-of-discharge condition is reached. As a result, the series string of cells is reduced by the affected cell voltage, however, normal operation of the remaining battery cells continue to provide power. As before, cell venting and catastrophic failure of the battery is unlikely.

[0039] The protection circuit of the preferred embodiment as described above also provides a number of other advantages as well. The protection circuit provides any one or more or all of the following advantages:

1. Prevents cell damage during depassivation discharge.
2. Prevents over depletion of battery charge for hazardous chemistry cells. The battery may be fully discharged in operation without over-discharge cell venting. This in turn, reduces the risk of chemical accidents.
3. Improves safety and restrictions during shipping and handling of assembled batteries.
4. Allows hard connection of batteries to a load without an inrush or cell reversal hazard.
5. Prevents cathode freeze-over due to excessive discharge currents.
6. May be configured to support pulse discharge loading while maintaining overload protection for each cell.
7. Allows any number of cells to be placed in series without loss of performance, or inducing a single point failure hazard.

8. Eliminates the need to add parallel strings to protect for loss of power resulting from the failure of a single cell.

9. Prevents loss of cell capacity due to excessive voltage depression during high discharge loading.

10. Greatly reduces the risk of cell venting during operation.

11. Distributes current limiter or power loss (heat) over the full battery volume. Lowered junction temperature results in better overall reliability.

12. Allows each cell to source current to its peak ability before limiting action is activated.

13. Low cost solution results from large production volume of circuit requiring only a few components.

13. Protection modules may be reused when depleted batteries are replaced.

[0040] The above discussion is meant to be illustrative of the principles and various embodiments of the present invention. Numerous variations and modifications will become apparent to those skilled in the art once the above disclosure is fully appreciated. It is intended that the following claims be interpreted to embrace all such variations and modifications.